32nd Annual INCOSE international symposium
hybrid event
Detroit, MI, USA
June 25 - 30, 2022

Oversimplification of Systems Engineering Goals, Processes, and Criteria in NASA Space Life Support

Harry W. Jones
NASA Ames Research Center,
Moffett Field, CA, 94035-0001
650 604-5518
harry.jones @nasa.gov

Abstract. This paper investigates the oversimplification of the inherently complex systems engineering process in space life support. The standard systems engineering process steps are described. The International Space Station (ISS) life support system is explained with its goals and performance criteria. Although it is not usually emphasized, the essential function of developing a hierarchy of systems and subsystems is to simplify the design process. The System Complexity Metric (SCM) shows how this divide-and-conquer approach also reduces the system complexity. The complete systems engineering process has many detailed steps. It is often simplified because of the effort required and the human limitations on working memory and decision span. Systems analysis demands slow, logical, and focused thinking but is often bypassed in favor of quick, intuitive, subconscious "gut feel." A study of 100 system designs found examples of 12 specific mental mistakes, such as ignoring stakeholder needs, and these mistakes are essentially oversimplifications of the systems engineering process. An analysis of space life support goals, options, criteria, and processes found 11 examples of oversimplifications in systems engineering, such as neglecting safety and cost. All these 11 oversimplifications could be traced to one or more of the 12 previously identified mental mistakes or other well-known ones, such as ignoring sunk costs. Oversimplification of the systems engineering process is rarely noticed but is a common and harmful problem. A study of failures in 50 different space systems found that problems in systems engineering caused failures and often led to errors in design, development, and test that further contributed to failure. It seems that more diligent systems engineering could prevent many project problems and failures, but projects seem to be more guided by "gut feel" based on tradition, authority, and consensus than on the logical, rational systems engineering approach.

Introduction

The standard systems engineering process is fundamentally necessary in designing life support and other space systems. It helps cope with complexity, which is a major challenge in system design, but engineering becomes more difficult as the complexity of the system increases. The systems engineering process deals with complexity in two ways. First it implements a logical hierarchy of subsystems each with less complexity, and second, it follows a sequential development process from requirements through architecture, design, technology trade-offs, test, and customer validation. However, the full recommended systems engineering process is extensive and usually is not carried out in full detail. There are several reasons for this. The difficulty and cost of the process grows with complexity. The systems engineering process may be simplified because of well-known cognitive limitations on memory span and working memory and by the propensity to use intuitive decision-making short cuts. And limitations of resources or urgent short-term problems often divert attention from longer term issues. In some cases, standard systems engineering can be seriously over-

simplified. The true system goals, the planned design effort, and the original trade-off criteria can be changed, reduced, or eliminated. Poor system performance and operational failures may result when systems engineering is oversimplified.

The Systems Engineering Process

The two foundations of systems engineering are hierarchical design using subsystems and sequentially phased engineering development. The usual top-down system design process produces a hierarchy of vertically interconnected systems with subsystems and subsubsystems at lower levels, creating a structure like an inverted tree. The purpose of this process is to reduce complexity and improve comprehension and decision making.

"The objective of systems engineering is to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule, and risk." (Shishko 1995, p. 4) The standard systems engineering process is described in many sources. The usual steps are shown in Table 1.

Table 1: The standard systems engineering process steps.

	Step
1	Requirements definition
2	Requirements flow down
3	Design options
4	Technology assessment
5	Systems analysis
6	Life Cycle Cost
7	Risk analysis
8	Safety analysis
9	System performance definition
10	Trade-offs and optimization
11	Integration
12	Test

(Shishko 1995, p. 4) (Blanchard and Fabrycky 1990) (NPR 7120.5B 2002) (Jones 2005-01-3006)

The requirements are based on the customer's needs. The requirements flow down defines the hierarchical system architecture and the design options are different implementations of the subsystems. Technology assessment provides detailed descriptions of the options and identifies gaps. Systems analysis considers the life cycle cost (LCC) elements and the schedule, risks, and performance baseline. The system performance baseline is used to determine the test plan, which can be considered to define the effective requirements. The trade-off studies compare candidate project design options considering performance, safety, cost, risk, and other criteria. They can be considered as producing an optimum solution, but only within the boundaries of the defined decision problem. The limits to knowledge and cognition suggest that the systems engineering process is satisficing rather than optimizing. Integration and test usually consume significant budget and schedule. Testing has two components, verification that the system meets its requirements and validation that it meets the customer's needs.

The system development process is difficult and not always successful. Some failures can be attributed to flaws in executing the standard systems engineering process.

Space Life Support System Design

The International Space Station (ISS) life support system uses extensive recycling. Upgrades are being planned and goals and criteria have been developed to guide research and development. The block diagram of the ISS life support system is shown in Figure 1.

The ISS life support system.

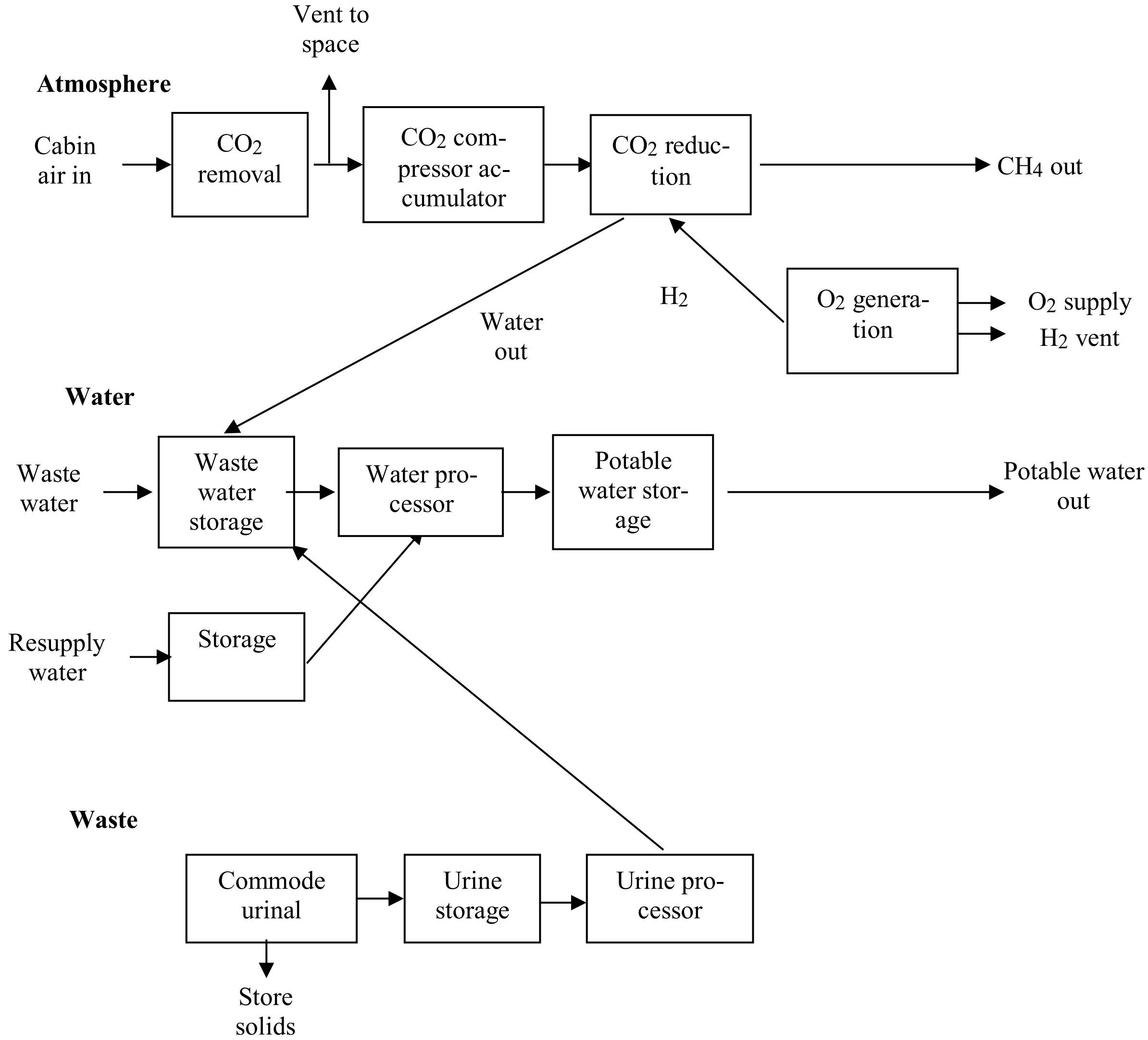

Figure 1. The ISS life support block diagram

The ISS life support system contains atmosphere, water and waste recycling processors. The five major subsystems are carbon dioxide removal, carbon dioxide reduction, oxygen generation, water processing, and urine processing. The four-bed molecular sieve (4BMS) carbon dioxide removal system is designed to allow the carbon dioxide to be vented to space or to be delivered to the Sabatier carbon dioxide reduction system. The electrolysis oxygen generator provides oxygen directly to the cabin atmosphere. The product hydrogen can be vented overboard or used for carbon dioxide reduction. Waste hygiene water and cabin condensate are stored and routed through the potable water processor to a potable storage tank. Resupply water delivered by Progress or other resupply vehicles is usually run through the water processor before potable use. Urine is pumped from the urinal to the urine processor and the urine distillate is combined with other wastewater. The commode compacts and bags feces. Solid wastes and feces are usually loaded into Progress or another vehicle and burned up during Earth reentry. (Carrasquillo and Bertotto, 1999) (Bagdigian and Ogle, 2001)

Goals and criteria. The most important goal of NASA space life support research and development is to have missions successfully fly new life support technology. A new technology can be expected to be adopted if it provides better safety, availability, performance, or cost. Improvements in these four criteria are the major supporting goals of life support research. According to an early life support

plan, ideal candidate technology would also provide increased self-sufficiency and closure, be useful on different types of missions, and have high potential for technology transfer, but these are secondary benefits that are not directly required for successful use in flight. (Advanced Life Support Program Plan 1998) Measuring progress toward all these independent and even conflicting goals requires that ALS use multiple metrics. (Jones 1999)

Taking the overall goal of life support R&D as the successful mission use of life support technology, The subgoals and criteria can be arranged as follows:

1. Safety
    1.1. # of criticality 1R failures
    1.2. Pr(LOC), Probability of Loss of Crew
2. Availability
    2.1. TRL, Technology Readiness Level
3. Performance
    3.1. Function
        3.1.1. quantity of product
        3.1.2. quality of product
    3.2. Other considerations
        3.2.1. microgravity
        3.2.2. un-crewed operations
        3.2.3. contamination
        3.2.4. noise
        3.2.5. radiation impact
        3.2.6. flexibility
        3.2.7. commonality
4. Cost
    4.1. LCC, Life Cycle Cost
        4.1.1. DDT&E cost
        4.1.2. Launch cost
        4.1.3. Operations cost
    4.2. ESM, Equivalent System Mass
        4.2.1. mass
        4.2.2. volume
        4.2.3. power
        4.2.4. cooling
        4.2.5. resupply and spares mass
    4.3. "-ilities"
        4.3.1. maintainability
        4.3.2. reliability
        4.3.3. SCM, System Complexity Metric
    4.4. crew time

(Jones 1999) (Abney et al. 2020) (Morrow et al. 2019)

Most of the suggested life support technology criteria are easily understood but some require explanation. In Failure Modes and Effects Analysis (FMEA), each system will have the criticalities of the potential failures rated. Criticality 1 occurs when a single failure point could result in injury or loss of life. The usual requirement for a manned space system is that there are no potential failures of criticality 1. Criticality 1R occurs when there are redundant hardware items, which if all failed could result in injury or loss of life. Operational life support systems may have several potential failures of criticality 1R. The traditional NASA requirement has been for two fault tolerance, which requires three redundant systems, but one fault tolerance is being considered for NASA current projects. The Probability of Loss of Crew, Pr(LOC), is computed using probabilistic risk analysis, which has been

required for NASA missions since Challenger. Improperly implemented redundancy may actually increase the probability of failure. (Ocampo 2014)

The availability of hardware for mission use is often measured by its Technology Readiness Level (TRL). Technologies with a TRL of less than 4, components validated in a laboratory, were not considered in ISS life support selection. The ISS systems are now at TRL 9, flight proven. The TRLs of good candidate technologies usually increase with time, as further research and development is funded. (Jones 1999)

Life Cycle Cost (LCC) includes the costs incurred during the design and development, launch and emplacement, and operations phases of a space mission. The cost for design, development, test and evaluation (DDT&E) can be estimated using the Advanced Missions Cost Model (AMCM) which is an equation depending on the factors of system dry mass, type of mission, hardware generation, and estimated difficulty. (Guerra and Shishko, 2000, pp. 946-7) The launch cost per kilogram has dropped significantly in the last decade and is available from launch organizations. For manned spacecraft, the operations cost per year is typically 11% of the total DDT&E and production cost. (Guerra and Shishko 2000, p. 938) (Jones 2003-01-2635)

The Equivalent System Mass (ESM) of a system is the sum of the estimated mass of the hardware, of its required materials and spares, and of the pressurized volume, power supply, and cooling system needed to support the hardware in space. The ESM and the launch cost per kilogram determine the launch cost. ESM has been prescribed for use as the major technology selection factor for life support technology since 1998. (Morrow et al. 2019) Its use is limited to NASA life Support, while LCC is used widely in NASA, aerospace, and industry. (Jones 2003-01-2635)

Coping with Design Complexity

The standard systems engineering process uses a hierarchy of subsystems and a sequence of development stages that usually seem directly obvious but are better explained as methods developed to cope with the complexity of systems design.

The System Complexity Metric (SCM). The SCM was developed to measure and help reduce complexity. The SCM is defined as the sum of the number of nodes, N, in the system block diagram plus the number of one-way interactions, I, between the nodes. SCM = N + I. The SCM increases at least linearly with N, and possibly as rapidly as the square of N, since each node may be connected to all the other nodes. The SCM is easily determined by direct inspection of schematics or block diagrams and can provide an early indication of relative system cost and reliability.

If a system has N = 100 nodes and is not divided into subsystems, its maximum SCM is N^2 = 10,000. If the system is divided into five subsystems, each has N = 20 nodes and each of them has a maximum SCM = 400. The five subsystems in the second level have a total subsystem SCM = 5 * 400 = 2,000 and the top-level system has five nodes and a maximum SCM = 25. By dividing the system into five subsystems, the maximum complexity has been reduced from 10,000 to 2,025, roughly by factor of five. (Jones 2020-223)

The SCM has been suggested as a replacement or augmentation for ESM in life support technology screening. (Jones 2020-223) A mass equivalent of crew time has been added to ESM but it creates complications. (Jones 2003-01-2635) The selection criteria that are not based on quantitative data are usually qualitatively estimated and scored. The scores are often combined into one overall score. (Abney et al. 2020) (Jones 2010-6015)

Human cognitive limitations. Psychological studies of human decision making have found serious limitations on human memory and decision processes. Herbert Simon is well known for introducing the concepts of bounded rationality and satisficing. Bounded rationality challenged the accepted

economic model of optimal rational decision making by emphasizing that both the available information and human analysis capabilities are limited. (Simon 1991, p. 125) Simon found three steps in decision making: identifying the alternatives, determining their outcomes, and evaluating their outcomes. Acceptable decision making with limited resources was called satisficing, in contrast to the accepted idea of economic optimizing. (Simon 1955, p. 99)

Miller showed that humans have a short-term memory of seven plus or minus items of information, such as random letters. (1956, p. 81) Memory capacity is smaller for more complicated ideas, but three to five complex "chunks," such as chess openings can be handled simultaneously. (Chase and Simon 1973 p. 55) (Cowan 2001) The limit on working memory capacity is not always due to the inability to recall information. Some multi-variable discrimination tests provide all the required data in written form but still the relations between three or more variables cannot be easily understood. Systems designed by humans are intended to be understood by humans, so the complexity of human designed systems is constrained by the limits on human cognition.

Use of Intuitive Methods in Decision Making

In addition to rational analysis, human beings use intuitive methods to cope with complexity. Some of these intuitive methods are called heuristics, which are simple, efficient, instinctive rules used to simplify decision making.

Kahneman's system 1 and system 2. In Daniel Kahneman's book, Thinking, Fast and Slow, he explains that humans use two modes of thinking, system 1 which is quick, intuitive, and unconscious or, in contrast, system 2 which is slow, logical, and focused. (Kahneman, 2011) Kahneman won the Nobel prize in economics for his work revising the fundamental assumption that humans were rational economic optimizers by adding instinctive thinking. Humans usually make decisions using system 1, fast intuitive thinking which is automatic, effortless, unguided, and unconscious. System 1 is used when the problem seems familiar and the decision obvious. System 2 is used when a problem appears complex and difficult to solve. System 2 allocates conscious attention to decisions that require effortful mental processing. (Kahneman 2011)

Investigations of system 1 show why much human behavior is not rational and explain some of the common human decision errors made using intuitive thinking. System 1 fast thinking usually jumps to an acceptable conclusion using some heuristic, a mental shortcut or instinctive rule-of-thumb that solves problems quickly without taking time to think. It relies on generally useful heuristics that are built into the human brain and produce familiar systematic errors in decision making. Heuristics described by Kahneman include anchoring, attribute substitution, availability, framing, loss aversion, overconfidence, and the sunk cost fallacy. (Kahneman 2011)

Decision making heuristics affecting systems engineering. Psychological experiments in decision making relate to the analysis and tradeoff studies in systems engineering, so systems engineering is susceptible to the human mental mistakes and biases of system 1. (Smith et al. 2007)

Kahneman found that many different cognitive biases belong to one higher-level bias, called attribute substitution. Attribute substitution occurs when the target attribute is unconscientiously replaced by a lower level attribute that is simpler or more easily accessible, while the original attribute and its other lower level attributes are ignored. This bias occurs frequently at all phases of the systems engineering process. (Smith and Bahill 2009)

A two-decade study of more than 100 system designs searched for examples of 28 specific mental mistakes. (Bohlman and Bahill 2014) While some types of mistakes are not recorded in the final documentation, the research found examples of the 12 mental mistakes shown in Table 2.

Table 2: 12 mental mistakes in systems engineering

12 Mental Mistakes
1. Using Dependent Criteria
2. Not Stating the Problem in Terms of Stakeholder Needs
3. Vague Problem Statement
4. Substituting a Related Attribute
5. Sensitivity Analysis Mistakes
6. Forer Effect
7. Weight of Importance Mistakes
8. Anchoring and the Status Quo
9. Treating Gains and Losses Equally
10. Not Using Scoring Functions
11. Implying False Precision
12. Obviating Expert Opinion

The criteria should be independent or organized hierarchically. In the earlier list of criteria, LCC is dependent on ESM through launch cost and ESM should probably be eliminated. Requirements often do not capture customer and stakeholder needs. The problem and goals should be stated clearly. Attribute substation is common, such as using ESM for cost or redundancy for reliability. Sensitivity analysis is almost always omitted. The Forer effect occurs in systems engineering when previously used criteria are adopted without much consideration because they appear to apply, are well developed, and have past authority supporting them. (Smith and Bahill 2009) The weights given to the decision criteria should be carefully considered. Anchoring occurs in numerical estimating because a first suggestion can bias all further estimates. The status quo should always be considered as an alternative, but it may be unduly preferred. Kahneman's prospect theory explains that subjectively, people weigh losses more heavily than gains, and this reduces customer's risk tolerance. (Smith and Bahill 2009) Weighting criteria scores and computing a combined score is recommended to provide an overall assessment. (Bohlman and Bahill 2014) False precision occurs when a score is given to several decimal places when the underlying data is less accurate. This gives an undue impression of accuracy and confidence. Engineers beginning a system development often start with a blank sheet, instead of consulting past work and experienced engineers.

Although these dozen common mental mistakes are continually repeated by engineers, teaching engineers about them can reduce their occurrence in the future. (Bohlman and Bahill 2014) These and other mental mistakes have led to oversimplification of the systems engineering process.

Oversimplification of goals, processes, and criteria

The oversimplification of space life support systems engineering is considered following the sequential steps of the systems engineering process. There are 11 identified systems engineering oversimplifications, numbered in the left column of Table 3. They are grouped as life support goals and requirements, options and alternatives, criteria and metrics, and processes. Each of the oversimplifications has the original systems engineering requirement, the simplification, the problem it caused, and the mental mistake that occurred. The numbers given the mental mistakes in Table 2 are shown. Three additional and well-known mental mistakes were also found. The references for Table 3 are in Table 4.

Table 3: Oversimplification of space life support systems engineering

	Life support goals and requirements			
	Original goal	Simplified goal	Problem	Mental mistake
1	Provide high quality, cost-efficient, and reliable astronaut life support	Increase system mass closure by recycling water, oxygen, etc.	Increasing closure has high cost and diminishing returns. Recycling for high closure is often not cost-effective.	2. Not Stating the Problem in Terms of Stakeholder Needs
2	Same	Reduce life support launch mass and cost by recycling.	Launch cost is now much lower than before. Other costs dominate LCC.	2. Not Stating the Problem in Terms of Stakeholder Needs 4. Attribute substitution
	Life support options and alternatives			
	Original options	Simplified options	Problem	Mental mistake
3	Improved ISS recycling life support versus Earth supply as on all other missions, Apollo to shuttle.	Consider only improved ISS life support for transit to Mars	Mars transit has more difficult reliability requirements and a shorter mission for recycling cost payback than ISS.	8. Anchoring to the Status Quo New. Not ignoring sunk cost. (Of the ISS life support development)
4	New option	Grow plants for all life support, food and air and water recycling	Plant chambers have much higher cost and mass.	2. Not Stating the Problem in Terms of Stakeholder Needs (Making use of plants the goal)
5	New option	Use biological water and waste processors to replace physical-chemical processors	Biological processors have much higher mass and process times than physical-chemical processors.	2. Not Stating the Problem in Terms of Stakeholder Needs (Making use of biology the goal.)
	Life support trade-off criteria and metrics			
	Original criteria	Simplified metric	Problem	Mental mistake
6	The criteria should include safety, availability, performance, and cost as described above.	ESM has been used alone as the major technology selection metric in life support.	ESM is a partial indicator of mission cost and omits LCC, performance, reliability, risk, etc.	4. Substituting a Related Attribute (Mass for cost.) 6. Forer effect 10. Not Using Scoring Functions (for all the criteria)
7	Same	SCM should be used as an indicator of cost and reliability.	SCM is a simple rough indicator of cost and reliability and does not reflect safety, availability, or performance.	4. Substituting a Related Attribute (Mass for cost.) 10. Not Using Scoring Functions (for all criteria).

8	Same	TRL is strongly relied on in selecting research investments.	Selecting one technology early and investing in it can be a self-fulfilling prediction.	8. Anchoring and the Status Quo. 10. Not Using Scoring Functions (for all criteria). 4. Substituting a Related Attribute
	Life support processes			
	Original process	Simplified process	Problem	Mental mistake
9	Standard systems engineering	Process replaced by management intuition and group consensus.	System engineering methods provide structure and help avoid errors. Intuition is often mistaken or biased.	New. Reliance on intuitive system 1 rather than analytic system 2.
10	Risk and safety analysis	Achieving one fault or two fault safe operation.	Redundancy may not improve reliability. Not all failures can be repaired with similar redundant components.	4. Substituting a Related Attribute. (Redundancy for reliability.)
11	Integrated testing	Only hours of integrated ISS life support testing were done.	Design and interface errors cause infant mortality and require time to trouble shoot. Long duration testing is needed to give confidence in failure rates and spares provision.	12. Obviating Expert Opinion. (On the need to test.) New. Overconfidence.

Table 4: References for Table 3 by row number

	References.
1	(Anderson and Stambaugh 2015), (Bilardo 1990), (Jones 2007-01-3221), (Jones 2007-01-3221), (Jones 2013-3362), (Jones 2013-3407), (Jones 2016-103), (Schneider and Shull 2017), (Wieland,1990).
2	(Jones 2003-01-2635), (Jones 2007-01-3221), (Jones 2015-295), (Jones 2017-87, (Jones 2018-58, (Jones 2018-81), (Jones 2019-17), (Jones 2020-223).
3	(Bagdigian 2015), (Jones 2017-85), (Jones et al. 2016), (Perry 2016), (Stromgren et al. 2017)
4	(Drysdale et al. 921241), (Gustan et al. 1983), (Gustavino 1991), (Hanford 1997), (Jones 2009-01-2466)
5	(Flynn et al. 1998), (Jones 2006-01-2082)
6	(Abney et al 2020) (Jones 1999-01-2079) (Morrow et al. 2019)
7	(Jones 2020-223)
8	(Jones 1999-01-2079)
9	(Abney et al 2020) (Jones 2005-01-3006), (Levri et al. 2003) (Morrow et al. 2019) (Kahneman 2011)
10	(Ocampo 2014-248)
11	(Jones 2005-01-3006), (Jones 2007-01-3144), (Jones 2012-3618), (Jones 2015-075), (Jones 2020-221).

Effects of Oversimplification in Space Life Support

The specific oversimplifications listed in Table 3 are discussed in more detail. The references are the same as those in Table 4.

1 High closure is the goal of space life support. After development of the ISS recycling life support recycling system, continued research and development was justified as needed to increase closure. The goal of life support research and development was to approach a totally closed human ecosystem, independent from Earth. The future life support system for the Moon and Mars was expected to include food production, waste recycling, and ultimately to be “totally closed except for losses due to leaks, EVA’s, etc.,” and to approach “complete closure of the food and solid waste loops.” (Wieland, 90-3728) (Bilardo, 90-3729) “The goal for these (Moon and Mars) missions is a higher level of mass recovery, perhaps achieving 95% closure.” (Wieland, 90-3728) However, the problem of diminishing returns indicates that achieving higher closure requires using technologies with lower cost-benefit, lower mass savings per dollar. The closure metric can be used to justify developing uneconomic technology to recover difficult scarce wastes or to grow food plants in space. Mental mistake: 2. Not Stating the Problem in Terms of Stakeholder Needs.

2 Reducing launch mass is the goal of space life support. In space life support, launch mass has been measured by the widely used ESM metric, discussed below. Making lower launch mass and launch cost the life support goal favors recycling technology over Earth supply, as does the above goal of increasing closure. Goal displacement is a form of attribute substitution. Mental mistakes: 2. Not Stating the Problem in Terms of Stakeholder Needs, 4. Attribute substitution.

3 ISS life support should be the basis of a Mars transit system. The environment of ISS in low Earth orbit with zero gravity is similar to the environment of Mars transit, although Mars transit will have higher radiation, decreasing sunlight, and much longer delays for resupply and return. Using ISS recycling life support for Mars transit does not always save launch mass and seems much more expensive and much less reliable than using stored supplies. Mental mistakes: 8. Anchoring to the Status Quo, New. Not ignoring sunk cost.

4 Growing plants will be useful for life support. Growing plants for astronaut food is extensively researched but seems uneconomical. The large mass and power of plant growth chambers makes growing food much more expensive than supplying food from Earth, even for decade-long missions. (Jones 2006-01-2082) In an early assessment it was specifically stated for a Mars surface mission that “it does not appear that CELSS (food plants) would benefit this mission.” (Gustan et al., 831149) Eckart’s detailed bioregenerative system modeling found that “a break-even point between regenerable P/C (physical/chemical) systems and hybrid/CELSS systems is unlikely, because they save only a little mass from food resupply while requiring much more resupply mass to keep the hardware systems for plant growth operating.” (Doll and Eckart, 2000, p. 566) Mental mistake: 2. Not Stating the Problem in Terms of Stakeholder Needs.

5 Biological water and waste processors will be useful for life support. In the 1990’s, NASA became interested in applying biology in space systems, including life support water recycling. This seemed reasonable when closure was the accepted life support metric but the later use of Equivalent System Mass (ESM) produced conflicting results. (Jones 2006-01-2082) The first, optimistic, in-house assessment favored a bioreactor water processor. A later analysis found that the bioreactor water processor had ESM similar to the ISS water system but was about seven times more massive than two alternate non-biological systems. (Flynn et al., 981538) Mental mistake: 2. Not Stating the Problem in Terms of Stakeholder Needs.

6 Reducing Equivalent System Mass (ESM) is the goal of space life support. ESM is the total launch mass needed to provide and support a system, including its mass, volume, power, cooling, and

the mass of materials and spares. ESM was made the basis for life support technology selection. (Maxwell and Drysdale, 2001-01-2365). However, ESM reflects only launch cost, neglecting hardware development cost and operations costs. Project planning should consider the entire system cost, the Life Cycle Cost (LCC). LCC includes development, launch, and operations costs. (Jones 2003-01-2635) For recycling life support systems, the development and operations cost is usually much larger than the launch cost. The use of ESM, like the use of closure, creates a bias in favor of using recycling systems over Earth supplied materials. Supplying all materials has very high launch mass and ESM but very low development cost for the materials and their containers. Recycling systems have much lower launch mass and ESM, but they have very high development cost for the recycling systems themselves. The LCC of life support recycling systems can be much higher than the LCC of storage systems. (Jones 2013-3407) (Jones 2012-3418) Recently much lower launch cost has reduced the portion of LCC due to ESM and has made Earth supply relatively more attractive than recycling. (Jones 2017-87) (Jones 2018-81) Mental mistakes: 4. Substituting a Related Attribute, Mass for cost, 6. Forer effect, using past criteria without reconsideration, 10. Not Using Scoring Functions for all the criteria.

7 The System Complexity Metric (SCM) should be used to select life support technology. The SCM reflects system complexity and is a rough indicator of cost and failure probability (Jones 2020-223) but relying on any single metric is attribute substitution. All the relevant criteria should be considered in technology selection. The qualitative criteria should be emphasized since there is a tendency to overweight quantitative criteria. (Smith and Bahill, 2009) Mental mistakes: 4. Substituting a Related Attribute (Mass for cost.), 10. Not Using Scoring Functions for all the criteria.

8 Technology Readiness Level (TRL). Unlike ESM and SCM, TRL is widely used in space and military technology research and development. The ultimate goal of research and development is to provide technologies and systems that meet customer needs, but there are intermediate TRL goals such as demonstrating feasibility and validating prototypes that can be substituted. Research efforts not funded by the customer can be characterized as technology push rather than demand pull. The "valley of death" is often used to describe the gap between research projects in the lab and mission hardware. Many workable innovations are eclipsed by better options and if so, the intended customer may not provide the anticipated demand. Mental mistakes: 8. Anchoring and the Status Quo, 10. Not Using Scoring Functions for all the criteria.

The best path to customer acceptance is to understand and meet customer needs. Intermediate goals such as the narrower, shorter-term TRL levels weaken the feedback loop from requirements to customer acceptance. Goal displacement is a form of attribute substitution. Mental mistake: 4. Substituting a Related Attribute.

9 Systems engineering and intuition. The standard systems engineering process is quite complex and is rarely followed completely. For instance, trade studies may not score and weight the criteria or use sensitivity analysis. Many consider the systems engineering process to be box checking and form filling and would prefer that key decisions be made intuitively by experts. Nevertheless, a fact-based logical systems engineering approach can reduce design errors and anticipate operational challenges. Mental mistake: New. Reliance on intuitive system 1 rather than analytic system 2.

10 Risk and safety. Probabilistic Risk Analysis (PRA) has been prescribed to estimate the Probability of Loss of Crew (Pr(LOC)) since Challenger, and risk and hazard analysis are also required. Oversimplification of reliability occurs when component failures are assumed to be the only cause of failure, ignoring design and operator errors, cascade failures, and unpredicted system level interactions. Further oversimplification occurs when it is assumed that all component failures can be repaired using redundant spares, ignoring common cause failures and externally caused failures. Mental mistake: 4. Substituting a Related Attribute, redundancy for reliability.

11 Testing. The major ISS life support systems, carbon dioxide removal, water recycling, and oxygen recovery, were protoflight systems with little testing before launch to ISS. The failure rates of these systems have been much greater than predicted and this has caused dissatisfaction with the protoflight approach. The more costly traditional approach builds qualification and test units in addition to flight units. The test units are used to find, analyze, and fix failure modes. (Jones 2021-138) Mental mistakes: 12. Obviating Expert Opinion on the need to test, New. Overconfidence.

Review of the mental mistakes in space life support. The 12 mental mistakes found by (Bohlman and Bahill 2014) in their study of 100 design projects were listed in Table 2. Only 6 of these 12 were found in the Table 3 list of the systems engineering oversimplifications in space life support. These 6 mental mistakes are numbers 2, 4, 6, 8, 10, and 12. The other 6 not found usually occur in the standard systems engineering trade-off processes of defining criteria, weighting them, and defining their precision and sensitivity. These mental mistakes are not found because these steps were not done. Three new well-known mental mistakes not listed by Bohlman and Bahill were found in Table 3. They are failing to ignore sunk cost, relying on intuition, and over confidence.

Overall, 19 instances of mental mistakes were made in the 11 systems engineering steps in Table 3. Many mental mistakes were repeated. There were 5 instances, 26%, of mental mistake 4, Substituting a Related Attribute; 4 instances, 21%, of mental mistake 2, Not Stating the Problem in Terms of Stakeholder Needs; 3 instances, 16%, of mental mistake 10, Not Using Scoring Functions; and 2 instances, 11% of mental mistake 8, Anchoring and the Status Quo. The other 5 mental mistakes each occurred only once.

Why Does Oversimplification of Systems Engineering Occur?

Oversimplification is obvious and harmful. Most complex projects do some systems engineering but few use the process to the full extent possible. The intuitive methods and mental models used to oversimplify systems engineering are widely used in all types of decision making. Oversimplification in space life support has caused many harmful effects. But even though it seems to be widespread, pervasive, and damaging, oversimplification of the systems engineering process has not been identified as a specific known problem.

It is not usual to identify systems engineering errors as the cause of system failures. A typical failure investigation process starts with its immediate operational cause and does not trace back to consider possible initial systems engineering causes. It would seem better to trace the causes back from operations to manufacturing, then to design, and ultimately to systems engineering and project management.

System failures are often due to systems engineering causes. Newman used a systems engineering approach to analyze the causes of failure for 50 different space systems (2001). These systems had 94 specific failure causes that fell in ten different groups: 19 or 13% program and systems engineering management, 32 or 35% design and design test, 8 or 16% software and software test, 26 or 52% manufacturing and manufacturing test, 4 or 8% planning, and 5 or 10% policy, cost, and schedule. A failed system typically had two failure causes. Of the 19 systems with program and systems engineering management failure causes, all but 2 had one or more other failure causes. This is not surprising, since in addition to the specific systems engineering tasks, a main purpose of systems engineering is to help guide the later project phases. Newman observed that the wide variety of failure causes showed “the need for a systems engineering solution,” and “Anything less than the full measure of systems engineering rigor will expose the project to failure.”

Why are oversimplifications accepted? The usual expectation of using the standard systems engineering process should prevent oversimplifications and correct mental mistakes, while critical reviews of the process should detect errors. Oversimplification is accepted because the expected logical systems engineering process is neglected in favor of a more intuitive reliance on past tradi-

tion, management authority, and group consensus. The pragmatist American philosopher, Charles Sanders Peirce, described the four methods that people use to determine their beliefs: tradition, authority, consensus, and reason (1877). By reason, Pierce meant the scientific method, which he held was the only method of the four that admits it can make mistakes, that therefor criticizes and tests itself, and so shows that it is the only one designed to find the truth rather than agreement. Pierce conceded that the rational approach was slow and contentious and that this made it dangerously inferior to the other methods in urgent and critical situations. (Wikipedia, 2022) Tradition, authority, and consensus are natural, intuitive, and effective in decision making and should be used where appropriate.

Tradition, management authority, and group consensus all have been used to oversimplify space life support. The design of the ISS life support system can be considered traditional, since the first human closed chamber test of life support used similar architecture and technology and was conducted in the 1960's. Five decades of engineering progress, such as in control and automation, have been investigated but not incorporated in the currently accepted recycling life support design. (Jones, 2019-12) NASA life support management has exercised its authority to establish ESM as its major technology selection metric, while upper management has identified improved ISS life support as the expected approach for transit to Mars. The life support community including NASA and other space agencies, industry, and universities has supported most of the oversimplifications mentioned here in a long-term consensus.

Conclusion

The systems engineering process has been drastically oversimplified during the research and development of space life support. The assumptions, processes, and conclusions have been established by common everyday decision processes rather than developed logically and then rationally criticized. The systems engineering process is accepted as an ideal but is ignored in day-to-day project management.

This is not usually acknowledged but it can be explained. The systems engineering process has two aspects. It includes a list of recommendations to avoid known problems, such as not getting stakeholder support. It also guides an idealized project sequential flow. The extensive set of known problems usually includes some that are not relevant to the current project. And even if all the known systems engineering problems could be avoided, achieving this would not guarantee project success. Projects fail for many reasons, such as loss of management support, unsolvable technical problems, stronger competition, and situational change. Project management must often deal with more critical and urgent problems than those of systems engineering. Furthermore, systems engineering's focus on preventing potential problems can create a negative impression that impairs project advocacy. The near exclusive focus on reducing the mass of recycling life support was intended to avoid discussion of its high cost.

A potential project failure is often first apparent as an interruption in the ideal project sequential flow. Subsystems underperform or fail integration and test. Their redesign requires looping back to an earlier project stage, which greatly increases cost and schedule. The need for optimistic project advocacy often prevents contingency planning or realistic estimation of cost and schedule. The compelling reason for oversimplifying systems engineering may be to avoid the damaging impact of a realistic assessment of potential project problems.

References

Abney, M.B., Schneider, W. Brown, B., Stanley, C., Lange, K., Wetzel, J., Morrow, R., and Gatens, R., “Comparison of Exploration Oxygen Recovery Technology Options Using ESM and LSMAC,” ICES-2020-108, 2020.

Advanced Life Support Program Plan, Crew and Thermal Systems Division, JSC 39168, NASA, Sept. 30, 1998.

Anderson, M. S., and Stambaugh, I. C., “Exploring Life Support Architectures for Evolution of Deep Space Human Exploration,”2015-235, 45th International Conference on Environmental Systems, 2015.

Bagdigian, R. M., Dake, J., Gentry, G., and Gault, M., “International Space Station Environmental Control and Life Support System Mass and Crewtime Utilization In Comparison to a Long Duration Human Space Exploration Mission,” ICES-2015-094, 45th International Conference on Environmental Systems 12-16 July 2015, Bellevue, Washington.

Bagdigian. R. M., and Ogle, K., Y., “International Space Station Node 3 Environmental Control and Life Support System Status,” SAE Technical Paper 2001-01-2387, 31st ICES (International Conference on Environmental Systems), 2001.

Bilardo, V. J., Jr., “The Physical/Chemical Closed-Loop Life Support Research Project,” AIAA-90-3729, AIAA Space Programs and Technologies Conference, September 25-28, 1990, Huntsville, AL.

Blanchard, B. S., and W. J. Fabrycky, Systems Engineering and Analysis, Prentice Hall, Englewood Cliffs, N.J, 1990.

Bohlman. J., and Bahill, A.T., “Examples of Mental Mistakes Made by Systems Engineers While Creating Tradeoff Studies,” Studies in Engineering and Technology, Redfame publishing, Vol. 1, No. 1; February 2014.

Carrasquillo, R. L., and Bertotto, D., “ECLSS Design for the International Space Station Nodes 2 & 3,” SAE Technical Paper 1999-01-2146, Society of Automotive Engineers, Warrendale, PA, 29th ICES (International Conference on Environmental Systems), 1999.

Chase, W.G., and Simon, H.A., “Perception in chess,” Cognitive Psychology 4 (1973), 55–81.

Cowan, N., “The magical number 4 in short-term memory: A reconsideration of mental storage capacity,” Behavioral and brain sciences, Cambridge University Press, 2001.

Drysdale, Alan, Mark Thomas, Mark Fresa, and Ray Wheeler, “OCAM - A CELSS Modeling Tool: Description and Results,” SAE Technical Paper No. 921241, Society of Automotive Engineers, Warrendale, PA, 22nd International Conference on Environmental Systems, 1992.

Flynn, M., Fisher, J., and Borchers, B., "An Evaluation of Potential Mars Transit Vehicle Water Treatment Systems," SAE 981538, 28th International Conference on Environmental Systems, 1998.

Guerra, L., and Shishko, R., “Estimating the Cost of Crewed Space Systems,” in W. J. Larson, and L. K. Pranke, eds., *Human Spaceflight: Mission Analysis and Design,* McGraw-Hill, New York, 2000.

Gustan, E. A., Vinopal, T.J., and Olson, R.L., “A Near-Term Mission for CELSS,” Proceedings of the 13th International Conference on Environmental Systems, ICES 831149, 1983.

Gustavino, S. R., “A Study of the Effects of Bioregenerative Technology on a Regenerative Life Support System,” Proceedings of the 21st International Conference on Environmental

Hanford, Anthony J., “Advanced Regenerative Life Support System Study,” JSC 38672, March 3, 1997.

Jones, H. (2005) “Systems Engineering in NASA’s R&TD Programs” 35th International Conference on Environmental Systems, SAE 2005-01-3006.

Jones, H. (2010) “Using radar charts to select life support technology,” AIAA-2010-6015, 40th ICES (International Conference on Environmental Systems), 2010.

Jones, H. W., “Equivalent Mass versus Life Cycle Cost for Life Support Technology Selection,” 2003-01-2635, 33rd ICES (International Conference on Environmental Systems), 2003.

Jones, H. W., Pace, G. S., and Fisher, J. W., "Managing Spacecraft Waste Using the Heat Melt Compactor (HMC)," AIAA 2013-3362, 43rd International Conference on Environmental Systems July 14-18, 2013, Vail, CO.

Jones, H., "Breakeven mission durations for physicochemical recycling to replace direct supply life support," SAE 2007-01-3221, 37th International Conference on Environmental Systems, SAE 2007.

Jones, H., "Comparison of Bioregenerative and Physical/Chemical Life Support Systems" 36th International Conference on Environmental Systems, SAE 2006-01-2082.

Jones, H., "Controls and Automation Research in Space Life Support," 2019-12, 49th International Conference on Environmental Systems, 7-11 July 2019, Boston, Massachusetts.

Jones, H., "Equivalent Mass (EM), Life Cycle Mass (LCM), and Mass (M) Metrics Compared in Advanced Life Support (ALS) Analysis," SAE 2004-01-2363, 34th International Conference on Environmental Systems.

Jones, H., "Equivalent Mass versus Life Cycle Cost for Life Support Technology Selection," 2003-01-2635, 33rd ICES International Conference on Environmental Systems.

Jones, H., "Integrated Systems Testing of Spacecraft," SAE 2007-01-3144, 37th International Conference on Environmental Systems.

Jones, H., "Lessons Learned in Space Life Support System Testing," ICES-2021-138, 50th International Conference on Environmental Systems, 12-15 July 2021.

Jones, H., "Methods and Costs to Achieve Ultra Reliable Life Support," AIAA 2012-3618, 42nd International Conference on Environmental Systems, 15 - 19 July 2012, San Diego, California.

Jones, H., "Moon Base Life Support Design Depends on Launch Cost, Crew Size, and Mission Duration," 2019-17, 49th International Conference on Environmental Systems, 7-11 July 2019, Boston,

Jones, H., "Much Lower Launch Costs Make Resupply Cheaper Than Recycling for Space Life Support," ICES-2017-87, 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina.

Jones, H., "Multiple Metrics for Advanced Life Support," SAE 1999-01-2079, 29th International Conference on Environmental Systems, 2003.

Jones, H., "Multiple Metrics for Advanced Life Support," SAE 1999-01-2079, 29th International Conference on Environmental Systems.

Jones, H., "Reliability Growth in Space Life Support Systems," ICES-2014-075, 44th International Conference on Environmental Systems,13-17 July 2014, Tucson, Arizona.

Jones, H., "Starship Life Support," SAE 2009-01-2466, 39th International Conference on Environmental Systems, 2009.

Jones, H., "Storage or Recycling Life Support for Mars?" AIAA 2013-3407, 43rd International Conference on Environmental Systems, July 14- 14-18, 2013, Vail, CO.

Jones, H., "Systems Engineering in NASA's R&TD Programs," SAE 2005-01-3006, 35th International Conference on Environmental Systems.

Jones, H., "The Future Impact of Much Lower Launch Cost," ICES-2018-58, 48th International Conference on Environmental Systems, 8-12 July 2018, Albuquerque, New Mexico.

Jones, H., "The Life Cycle Cost (LCC) of Life Support Recycling and Resupply," 45th International Conference on Environmental Systems, ICES-2015-295 ,12-16 July 2015, Bellevue, Washington.

Jones, H., "The Recent Large Reduction in Space Launch Cost," ICES-2018-81, 48th International Conference on Environmental Systems, 8-12 July 2018, Albuquerque, New Mexico.

Jones, H., "The System Complexity Metric (SCM) Predicts System Costs and Failure Rates," ICES-2020-223, 50th International Conference on Environmental Systems, 12-16 July 2020,

Jones, H., "The System Complexity Metric (SCM) Predicts System Costs and Failure Rates," ICES 2020-223, International Conference on Environmental Systems, ICES 2020.

Jones, H., “Using the International Space Station (ISS) Oxygen Generation Assembly (OGA) Is Not Feasible for Mars Transit,” ICES-2016-103, 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria.

Jones, H., “Verified Cost-Effective High Reliability for New Deep Space Systems,” ICES-2020-221, International Conference on Environmental Systems, 2020.

Jones, H., “When Does Life Support Recycling in Space Save Cost?,” ICES-2014-071, submitted to 44th International Conference on Environmental Systems, 13-17 July 2014.

Jones, H., “Would Current International Space Station (ISS) Recycling Life Support Systems Save Mass on a Mars Transit?” ICES-2017-85, 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina.

Jones, H., Hodgson, E., Gentry, G., and Kliss, M., “How Do Lessons Learned on the International Space Station (ISS) Help Plan Life Support for Mars?” ICES 2016-105, 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria.

Kahneman, D., Thinking, Fast and Slow, Farrar, Straus, and Giroux, New York, 2011.

Levri, J. A., Drysdale, A. E., Ewert, M. K., Fisher, J. W., Hanford, A. J., Hogan, J. A., Jones, H. W., Joshi, J. A., and Vaccari, D. A. (2003) Advanced Life Support Equivalent System Mass Guidelines Document, NASA/TM-2003-212278, National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California.

Miller, G.A., “The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information,” Psychological Rev., Vol. 63, pp. 81–97, 1956.

Morrow, R.C., Wetzel, J.P., and Loyd, C., “Expanded Set of Criteria for Life Support Comparative Assessment,” 49th International Conference on Environmental Systems, 7-11 July 2019, Boston, Massachusetts.

Newman, J.S., “Failure-Space: A systems engineering look at 50 space system failures,” Acta Astronautica, vol. 48, no. 5, pp. 517–527, Mar. 2001.

NPR 7120.5B, NASA Program and Project Management Processes and Requirements, November 21, 2002.

Ocampo, R.P., “Limitations of Spacecraft Redundancy: A Case Study Analysis,” ICES-2014-248, 44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona.

Perry, Jay L., Miriam J. Sargusingh, and Nikzad Toomarian, “Guiding Requirements for Designing Life Support System Architectures for Crewed Exploration Missions beyond Low-Earth Orbit,” AIAA SPACE 2016 (p. 5461).

Peirce, C.S., *The Fixation of Belief*, 1877, https://en.wikisource.org/wiki/The_Fixation_of_Belief, accessed March 17, 2022.

Schneider, W., Shull, S. A., “NASA Advanced Explorations Systems: 2017 Advancements in Life Support Systems,” AIAA 2017-5152, AIAA SPACE and Astronautics Forum and Exposition, 12 - 14 Sep 2017, Orlando, FL.

Shishko, R., NASA Systems Engineering Handbook, NASA-SP-6105, June 1995.

Simon, H.A., “A behavioral model of rational choice,” Quarterly Journal of Economics, 59, 99–118, 1955.

Simon, H., "Bounded Rationality and Organizational Learning," Organization Science. 2 (1): 125–134, 1991.

Smith, E.D., and Bahill, A.T., “Attribute substitution in systems engineering,” Systems engineering, 2009.

Smith, E.D., Son, Y.S., Piattelli-Palmarini, M., and Bahill, A.T., “Ameliorating mental mistakes in tradeoff studies,” Systems Engineering, Vol. 10, No. 3, 2007.

Stromgren, C., Escobar, F., Anderson,, M. S., Stambaugh, I., Sargusingh, M. J., and Goodliff, K. E., “Assessment of Desired ECLSS Closure Rates for Human Mars Missions, AIAA 2017-5123,

Wieland, P., “ECLSS Development for Future Space Missions,” AlAA-90-3728, AIAA Space Programs and Technologies Conference, September 25-28, 1990, Huntsville, AL.

Wikipedia, “Charles Sanders Peirce,” https://en.wikipedia.org/wiki/Charles_Sanders_Peirce#, accessed March 17, 2022.